X-Ray Near-Field Speckle Based Wavefront Metrology

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Key Points

- X-ray near-field speckle based wavefront metrology offers a simple and affordable setup with high sensitivity and micrometer spatial resolution.
- We developed XST(X-ray speckle tracking) and XSVT (X-ray speckle vector tracking) methods that offer superior performance in comparison to conventional methods.
- Our methods can be used in X-ray beam wavefront metrology and X-ray optic characterization.

Introduction

- Modern synchrotron radiation sources provide coherent and extremely bright X-ray beams. The quality of the beam delivered to the sample is limited by the optics' imperfections and misalignment. Since the mechanical and thermal strains imposed by beamline operation cannot be perfectly modelled, ex-situ characterizations do not allow perfect predictions of their beamline performance. In-situ at-wavelength characterization is the natural way to overcome this limitation. In-situ wavefront sensing performed at the optics' operating wavelength ("at-wavelength" metrology) can be used not only to optimize the performance of X-ray optics, but also to correct and minimize the collective distortions of upstream beamline optics.[1]
- **X-ray near-field speckle-based phase-sensing methods** are amongst the most recent approaches introduced for online X-ray at-wavelength metrology. Some important advantages of these methods have already been demonstrated, such as the high angular sensitivity and simplicity of experimental implementation. Using partially coherent light from a synchrotron source, these methods have been shown to be fast, efficient and accurate while the feasibility of applying the methods at laboratory sources has also been validated.[2]

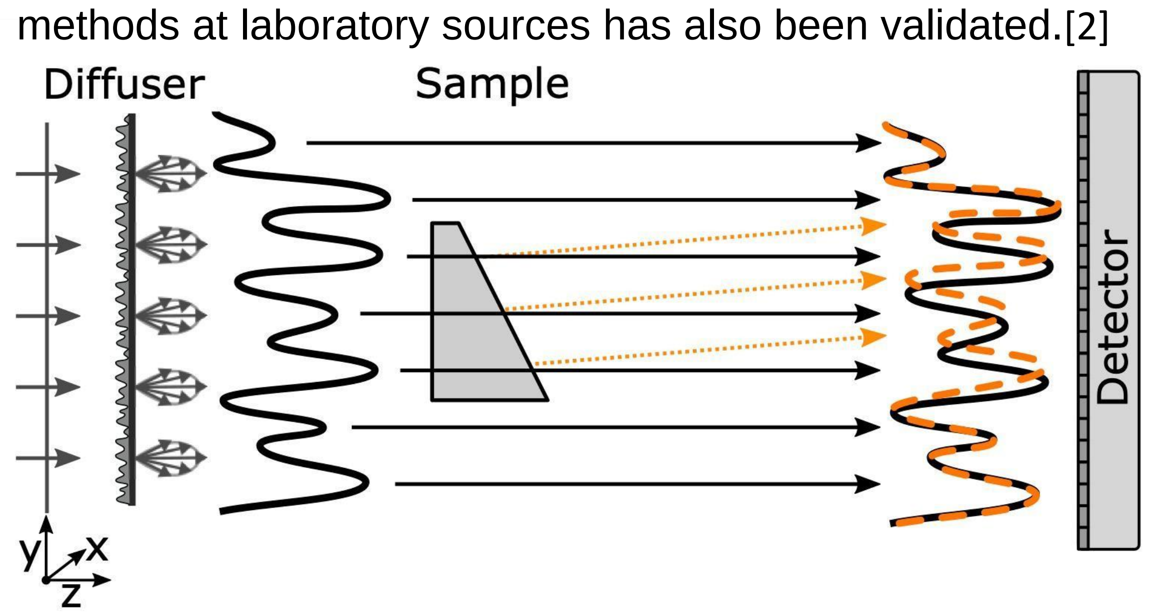

Figure 1. Principle of X-ray near-field speckle-based phase-sensing. Partially coherent x-rays are randomly scattered by the diffuser and mutually interfere to create a random intensity pattern (black solid line). Phase shifts from a sample cause a measurable displacement of the original speckle pattern (orange dashed line), corresponding to the phase-contrast signal.

In this study, we **(i)** develop XST and XSVT methods, and **(ii)** investigate the performance characteristics in comparison to ex-situ methods.

Methods

1. Phase-sensing using x-ray speckles

The gradient of the phase shift Φ introduced by the sample is proportional to refraction angle α, which is related to the speckle displacement vector **u** in small-angle approximation:

$$\left(\frac{\partial\Phi}{\partial x},\frac{\partial\Phi}{\partial y}\right)=\frac{2\pi}{\lambda}(\alpha_x,\alpha_y)=\frac{2\pi}{\lambda}(u_x,u_y)\frac{p}{d},$$

where λ is the x-ray wavelength, p is the detector pixel pitch, and d is the sample-detector distance.

2. XST method: In the XST technique, small pixel subsets from images taken at different propagation planes or different times are tracked using a numerical cross-correlation algorithm providing sub-pixel accuracy. In this mode, each subset of speckle patterns acts as a marker of the ray path that allows the recovery of the photon trajectories. One interesting aspect of this technique is that only one exposure of the optics is necessary to evaluate its performance while a reference image is taken without the optics in the beam. This permits an optic to be monitored over time.[1]

3. XSVT method: In XSVT scanning technique, two sets of multiple images are collected at different transverse positions (initially randomly chosen) of the diffuser. During the acquisition of the data sets of sample and reference, signals are built repeating the very same scan with and without sample in the beam, then signals are reorganized into a three-dimensional array by stacking the images. Figure 2 shows the stacking up of images when the sample is present in the beam. Data analysis starts by building two speckle vectors for each pixel using the two image stacks. Then, each vector from the sample stack is tracked across those of the reference stack. The location of the peak of maximum correlation between the sample vectors and the reference ones provides a mean of recovering the local displacement vectors; hence the differential phase gradient induced by the sample.[3]

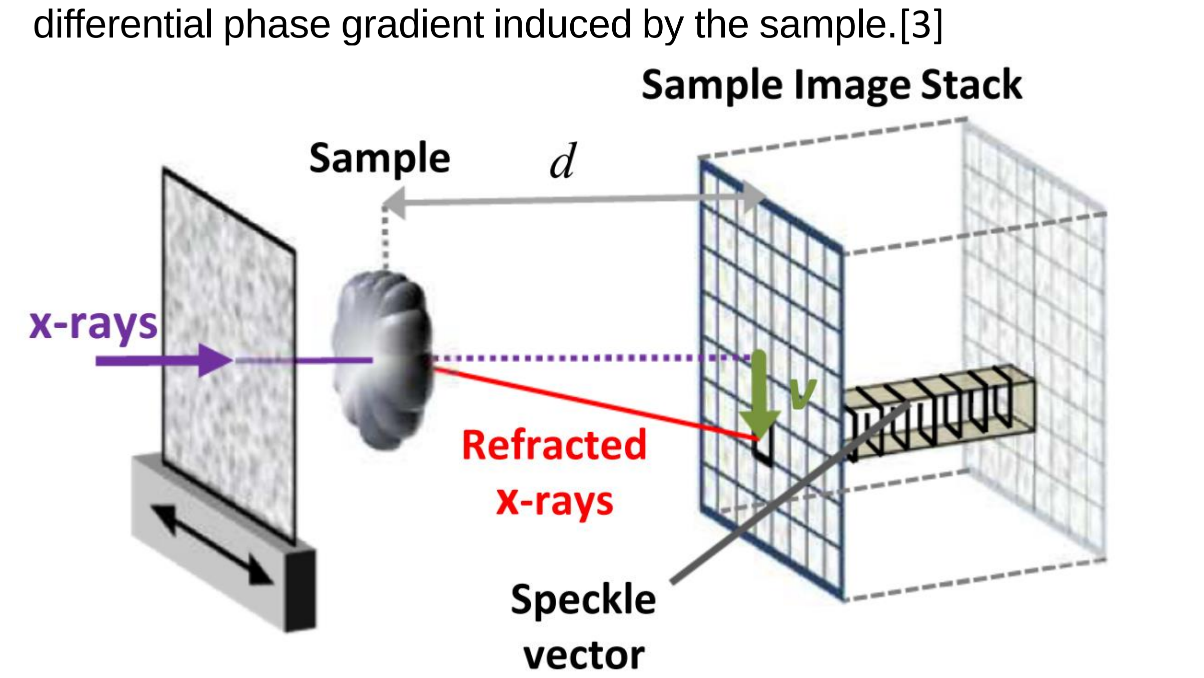

Figure 2. Conceptual sketches showing the data recorded and processed within XSVT scheme.

4. Speckle tracking algorithms

i. **Zero-normalized cross-correlation (ZNCC) for XST:** Small patches from the reference image are compared against a template region from the sample image and displacement is calculated through cross-correlation maximization.

ii. **Cosine similarity for XSVT:** Cosine similarity measures the similarity between two vectors in a multidimensional space. It is measured by the cosine of the angle between two vectors and determines whether two vectors are pointing in roughly the same direction.

iii. **Sub-pixel displacement registration algorithm:** The techniques described above only provide displacements with pixel level accuracy. To further improve the accuracy of digital image correlation(DIC), peak-finding algorithm is used.[4]

Results

- A compound refractive lens(CRL) was characterized using XST method**(Figure 3A).**
- The results are compared to the ones obtained using a confocal laser scanning microscopy**(Figure 3B**).
- A CRL was characterized using XSVT method**(Figure 4**).

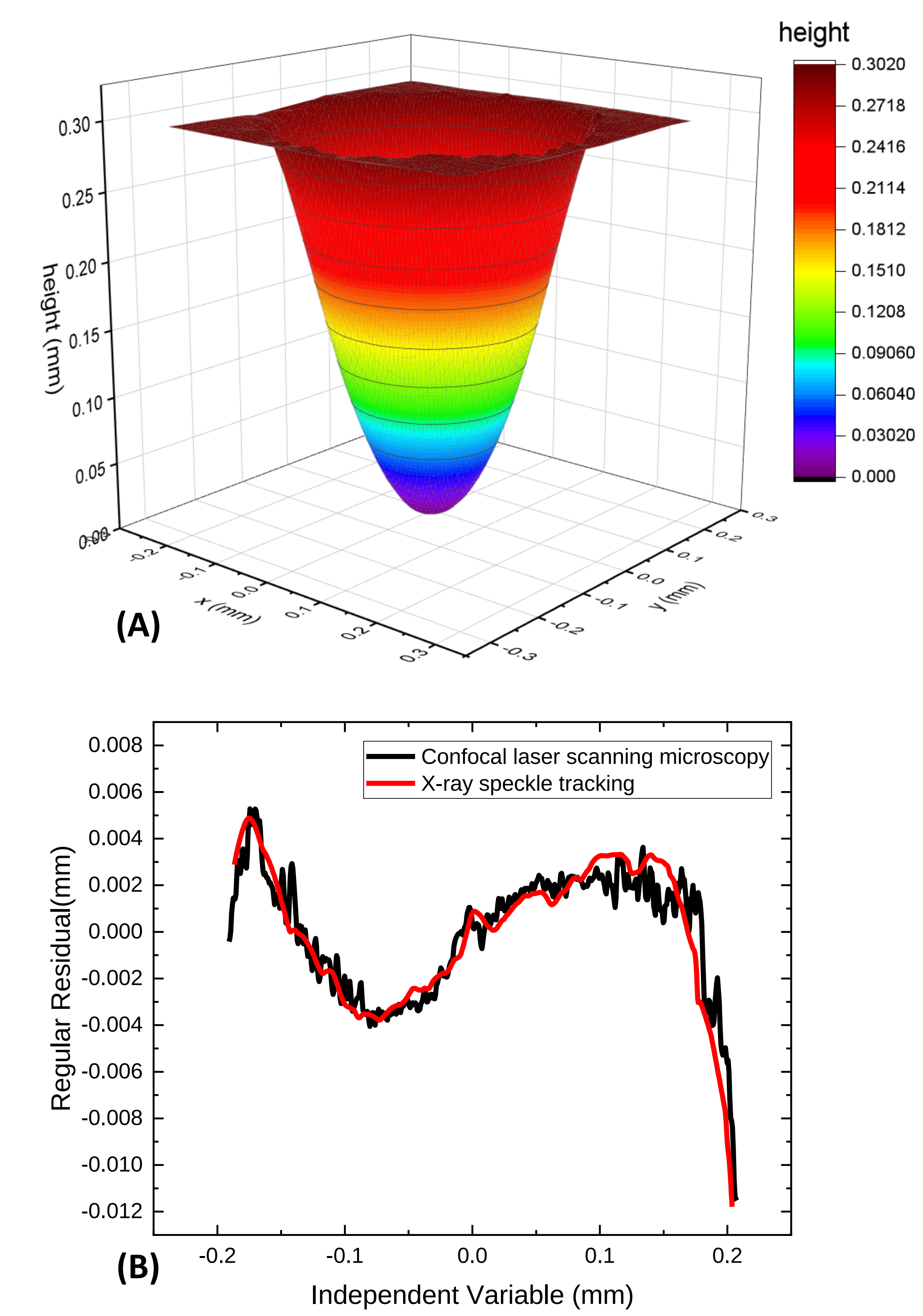

Figure 3. CRL detected by XST. (**A**) Profile detection result of CRL. (**B**) Comparison of XST and confocal laser scanning microscopy detection results.

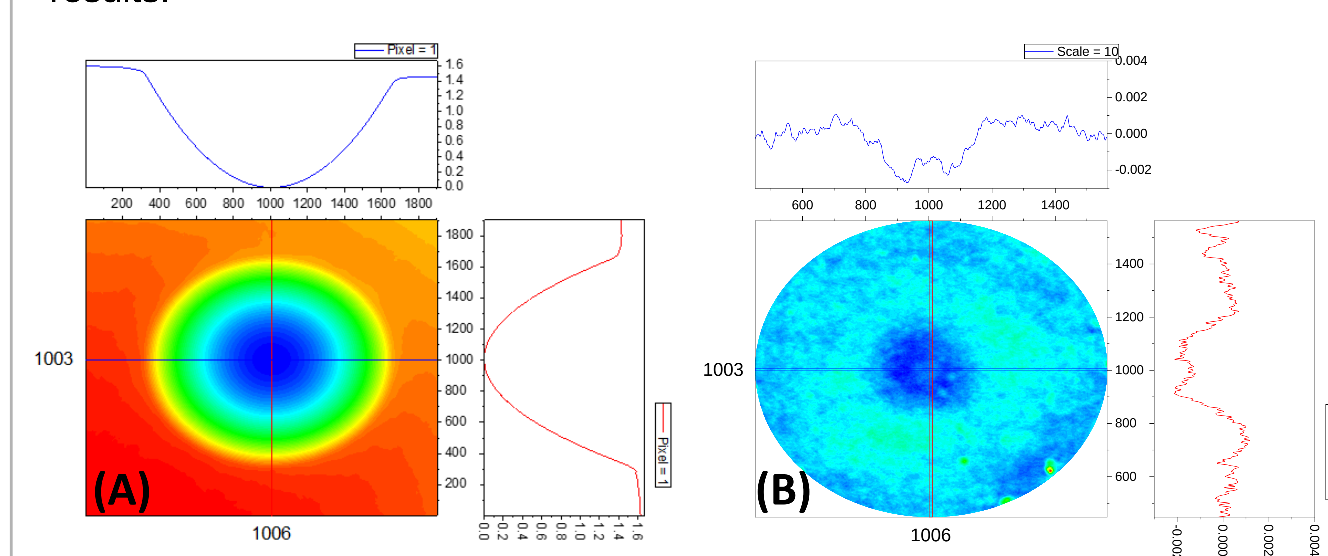

Figure 4. CRL detected by XSVT. (**A**) Profile detection result of CRL. (**B**) Regular residuals of CRL profile.

Conclusion

It has been demonstrated that the XST and XSVT techniques are well suited for the online characterization of optical components. The two-dimensional information obtained with the techniques allows rapid wavefront reconstruction, with very high sensitivity and micrometer spatial resolution.

References

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